Population of dynamically formed triples in dense stellar systems

Natalia Ivanova

Physics and Astronomy, Northwestern University, 2145 Sheridan Rd, Evanston, IL 60208 USA nata@northwestern.edu

Summary. In dense stellar systems, frequent dynamical interactions between binaries lead to the formation of multiple systems. In this contribution we discuss the dynamical formation of hierarchically stable triples: the formation rate, main characteristics of dynamically formed population of triples and the impact of the triples formation on the population of close binaries. In particular, we estimate how much the population of blue stragglers and compact binaries could be affected.

1 Introduction

In globular clusters, the most plausible way for the dynamical formation of hierarchical triples is via binary-binary encounters. As numerical scattering calculations show, the probability of triple formation is quite substantial and for equal masses, a hierarchical triple is formed in roughly 50% of all encounters (Heggie & Hut 2003). The probability is reduced by only a factor of a few when original semi-major axis of binaries are about equal (Mikkola 1984). The consideration of stars as non-point masses can decrease this probability further, as the physical collisions enhance strongly the destruction of close binaries during binary-binary encounters (Fregeau et al. 2004). The triple formation have often been noticed in numerical simulations of dense stellar systems using $N-$body codes (e.g., McMillan et al. 1991, Hurley et al. 2005), however so far there has been no attempt to study in detail the population of triple systems as well as their effect on the close binaries and blue stragglers. In this contribution we report the preliminary results of our triples population study.

2 Method and assumptions

We use a *Monte Carlo* method described in detail in Ivanova et al. 2005. This method assumes a static cluster background and that all relevant dynamical parameters are kept constant throughout dynamical simulation. In particular, the cluster model we consider here has central density $n_{\rm c} = 10^5$ [pc^{-3}], velocity dispersion $\sigma = 10$ [km/s], escape velocity $v_{\rm esc}$ [km/s] and half-mass relaxation time $t_{\rm rh} = 10^9$ [yr]. The code takes into account such important

dynamical processes as mass segregation and evaporation, recoil, physical collisions, tidal captures, and binary–single and binary–binary encounters. For dynamical encounters that involve binaries we use `Fewbody`, a numerical toolkit for direct N-body integrations of small-N gravitational dynamics (Fregeau et al. 2004). This toolkit is particularly suited to automatically recognize a hierarchical triple (formed via an encounter) using the stability criterion from Mardling & Aarseth (2001). In order to get large statistics on triples formation rate, we start with 1.25×10^6 stars, 100% are in primordial binaries; the modeled cluster has mass $\sim 250,000 M_\odot$ at 10 Gyr and the core mass is 10-20% of the total cluster mass. This cluster model represents well a "typical" globular cluster.

There is no developed population synthesis methods for triples evolution and as a result we can not keep the triples once they were formed. In our standard runs, we break a triple conserving the energy: the energy required to eject the outer companion is acquired from shrinking of the inner binary orbit. The outer companion is released unless the inner binary merges during shrinkage. In the latter case the inner system is allowed to merge and the outer companion is kept at its new, wider orbit to form the final binary system. This treatment prevents the possible eccentricity increase via the Kozai mechanism (Kozai 1962), which causes large variations in the eccentricity and inclination of the star orbits and could drive the inner binary of the triple system to merge before next interaction with other stars. To check this effect on the binary population, we compare two cluster models, with the completely the same initial population of 5×10^5 stars. In one model we use our standard treatment for triples breaking. In the second model we compare the Kozai time-scale $\tau_{\rm Koz}$ (taken as in Innanen et al. 1997) and the collision time-scale $\tau_{\rm coll}$ and inner binaries in the formed triples are merged if $\tau_{\rm Koz} < \tau_{\rm coll}$ (we define these triples as Kozai triples). We expect that some of the triples can also have a secular eccentricity evolution (see e.g. Ford et al. 2000), but we neglect this possibility.

3 Numerical results on dynamically formed triples

3.1 Formation rates

From our standard model, we find that a "typical" cluster has about 5000 hierarchically stable triples formed in its core throughout its evolution. As our triples are formed via-binary-binary encounters, the resulting formation rate intrinsically depends on the binary fraction, the binary cross-section and the total number of binaries. In the result, the obtained formation rate can be written as:

$$\Delta N_{\rm tr}/N_{\rm bin} = 0.05 f_{\rm bin} \langle m_{\rm b} \rangle \langle a \rangle \text{ per Gyr.} \tag{1}$$

Here $f_{\rm bin}$ is the binary fraction, $\langle m_{\rm b} \rangle$ is the average binary mass and $\langle a \rangle$ is the average binary separation. In particular, at 10 Gyr $\langle m_{\rm b} \rangle \approx 1 M_\odot$, $\langle a \rangle \approx 10 R_\odot$ and $f_{\rm bin} \approx 10\%$. The formation rate at 10 Gyr is therefore such that as many as 5% of all core binaries have sucesfully participated in the formation of hierachically stable triples during 1 Gyr. We stress that the expression above is fitted to numerical simulations; it does not include directly the expected dependence on the core number density and velocity dispersion because only one set of these parameters was used in simulations.

The formation rate of triples can also be written as the function of the cluster age (for ages > 1 Gyr):

$$\Delta N_{\rm tr} = 600 \; T_9^{-1/3} \text{ per Gyr.} \tag{2}$$

Here T_9 is the cluster age in Gyr.

3.2 Masses, orbital periods and eccentricities

In Fig. (1) we show the distributions of the triples companions masses (the mass of the inner binary and of the outer companion), the inner and the outer orbital periods and the outer eccentricities, for all dynamically formed triples throughout the entire cluster evolution. The inner eccentricities did not show strong correlation with any other parameters and are distributed rather flatly. A "typical" triple has the mass ratio $M_3/(M_1+M_2) \approx 0.5 \pm 0.1$, the total mass if the inner binary is $M_1 + M_2 \approx 1.3 \pm 0.3 M_\odot$ (such a binary, if merges, will likely produce a blue straggler), $P_{\rm in} \approx 1$ day, high period ratio $P_{\rm out}/P_{\rm in} \approx 1000$, the ratio of the orbital separations $a_{\rm out}/a_{\rm in} \approx 100$ and very high outer eccentricity, $e_{\rm out} \approx 0.95 \pm 0.05$.

3.3 Hardness and the Kozai mechanism

Only these triples that have the binding energy of the inner binary with the outer companion greater than a kinetic energy of an average object in the field are stable against the following dynamical encounters (the ratio of these energies is the triple hardness, η). We find that 45% of all triples have $\eta > 1$ and only 7% of all triples have $\eta > 10$. In our numerical simulation we find that for binaries, to likely survive subsequent dynamical encounters, a hardness should be about few times larger than 1. Therefore we can assume that most of the formed triples can be easily destroyed in their subsequent evolution in the dense core. However, we find also that about a third of all triples are the Kozai triples. The probability that a triple is affected by Kozai mechanism does not correlate with the triple hardness, the orbital periods or the eccentricities. In the result, a significant fraction of all triples can evolve not as our triples breaking treatment predicts.

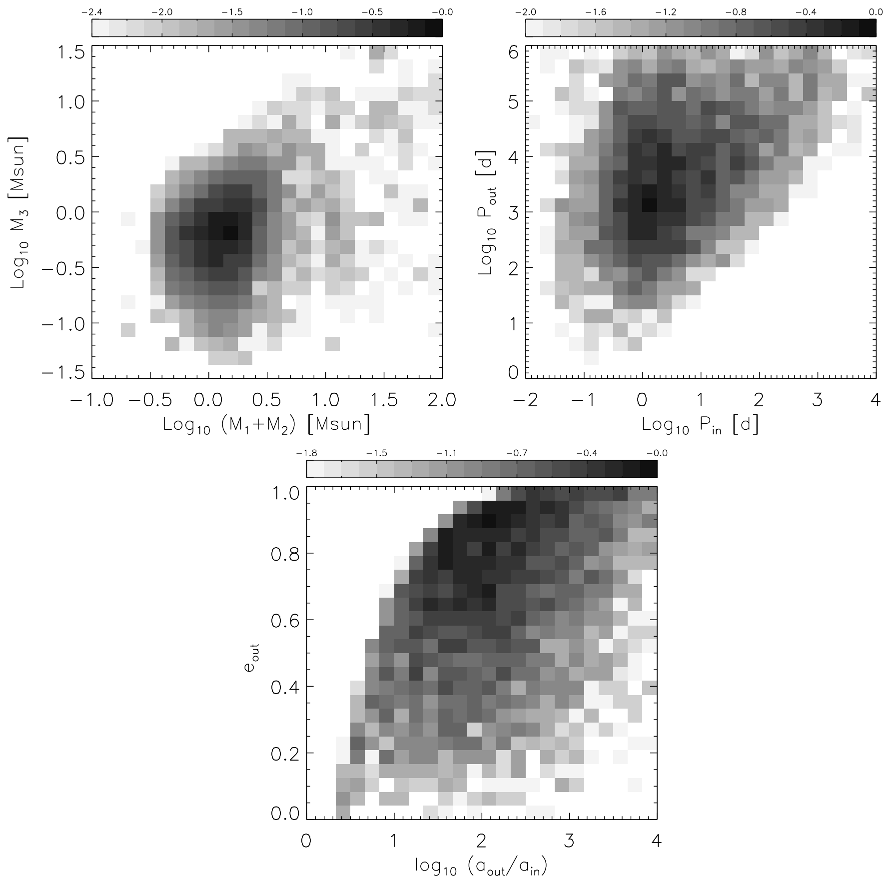

Fig. 1. The distributions of masses of inner binaries and the outer companions (the left panel), the inner and the outer orbital periods (the right panel) and the outer companion eccentricities versus the orbital separation ratio (the bottom panel) in the dynamically formed hierarchically stable triples. The colors correspond to the logarithm of the probability density.

3.4 Population of Kozai triples

About 60% of all triples have main sequence-main sequence inner binary and 30% of them are Kozai triples. A typical Kozai main sequence-main sequence binary has the total mass of the inner binary of $1.3 \pm 0.2\ M_\odot$ (see also Fig. 2). If Kozai mechanism leads to a merger, we find that these triples can provide 10% of all ever created blue stragglers.

About 40% of all triples have inner binary with a compact object and 35% (40% for white dwarf-white dwarf inner binaries) of them are Kozai triples. A typical white dwarf-main sequence binary affected by Kozai is 0.8 $M_\odot$ white dwarf and 0.8 $M_\odot$ main sequence star. It is not clear if the Kozai

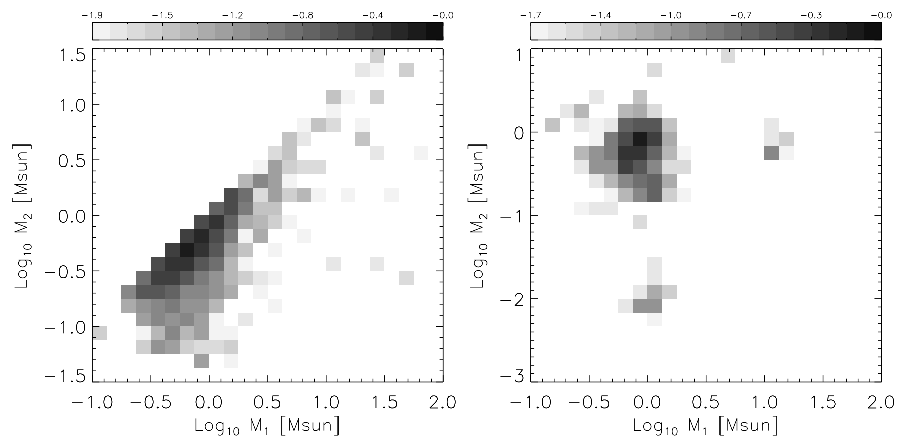

Fig. 2. The population of inner binaries in Kozai triples: main sequence-main sequence binaries (the left panel) and and inner binaries with a compact object (the right panel). The colors correspond to the logarithm of the probability density, M_1 is the mass of more massive companion in the case of main sequence-main sequence binary or the mass of a compact companion.

mechanism will lead to the merger or to the start of the mass transfer and create therefore a cataclysms variable. The formation rate per Gyr (at 10 Gyr age) corresponds to about 25-50% of present at this age cataclysms variables.

3.5 Comparison of the close binaries population and the triples population

Table 1. The stellar population of close binaries and triples in the cluster core at the age of 10 Gyr. MS is for a main sequence star, RG is for a red giant, WD is for a white dwarf and NS is for a neutron star.

	Binaries		Triples, inner	binaries	Triples, outer companions
	MS	WD	MS	WD	
MS	79%	13%	60%	20%	79%
RG	0.7%	0.3%	2%	1%	0.7%
WD		7%		15%	20%
NS	0.3%	0.3%	0.6%	0.7%	0.3%

In Table 1 we provide the complete statistics for the stellar population of close binaries and triples in the cluster core at the age of 10 Gyr. We find that the inner binary of a triple is more likely to contain a compact object than a core binary at 10 Gyr. Outer star follows the binaries populations.

3.6 Comparison of models with and without Kozai triples mergers.

We did not find that different treatments of Kozai triples (our standard breaking of triples based on the energy balance or the enforced merge of the inner binary if the triples is a Kozai triple) lead to significantly different results for the binary fractions (the difference is less than 1%). Some difference is noticed for the distribution of binary periods of core binaries with a white dwarf companion: in the model where Kozai triples, once formed, had their inner binaries merged, the relative number of binaries with the periods less than 0.3 day is smaller than in the model where Kozai triples were treated as usual, and for binaries with periods between 0.3 and 3 days the situation is reversed.

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